# Emissions from cochlear modelling

van Hengel, Pieter Willem Jan

# Part I

# The real cochlea

# Cochlear geometry

## 1.1 The overall structure of the cochlea

The cochlea in humans is an approximately 35 mm long tube coiled up in the shape of a snail shell. It is located inside the temporal bone, a rigid structure which protrudes into the skull at the ears (see Fig. 1).

Sound waves reaching a person's outer ear pass through the ear canal and the middle ear to reach the oval window of the cochlea. The cochlea is completely enclosed in the temporal bone and because it is filled with a practically incompressible fluid, motion of the oval window is only possible due to the presence of a second window: the round window, compensating the movement. The cochlear tube is divided into three channels or scalae by two membranes that extend over almost the entire length. Figure 2 indicates that the basilar membrane (BM) separates the scala tympani from the scala media, and Reissner's membrane separates the scala media from the scala vestibuli.

Generally it is assumed that only the basilar membrane and the structures it supports, together called the cochlear partition (CP), are of interest for the mechanics of the cochlea. Reissner's membrane is a thin layer of cells which only serves to keep the fluid in the scala vestibuli and the scala media apart. The fluid in scala media differs from the fluid in the other two scalae in chemical composition, probably serving the creation of electrical potentials. The fluid in scala vestibuli and scala tympani is called perilymph, the fluid in scala media endolymph. Mechanically they are both believed to be equivalent to water. Thus, the mechanical action of the cochlea is determined mainly by

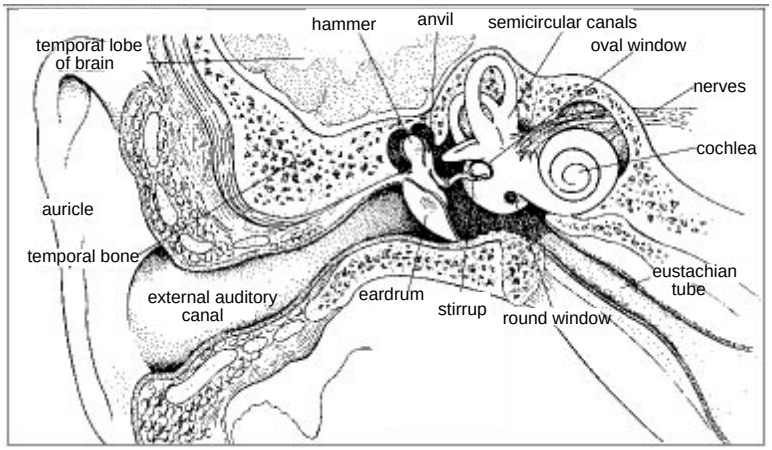


**Figure 1:** The outer, middle and inner ear in a human subject.

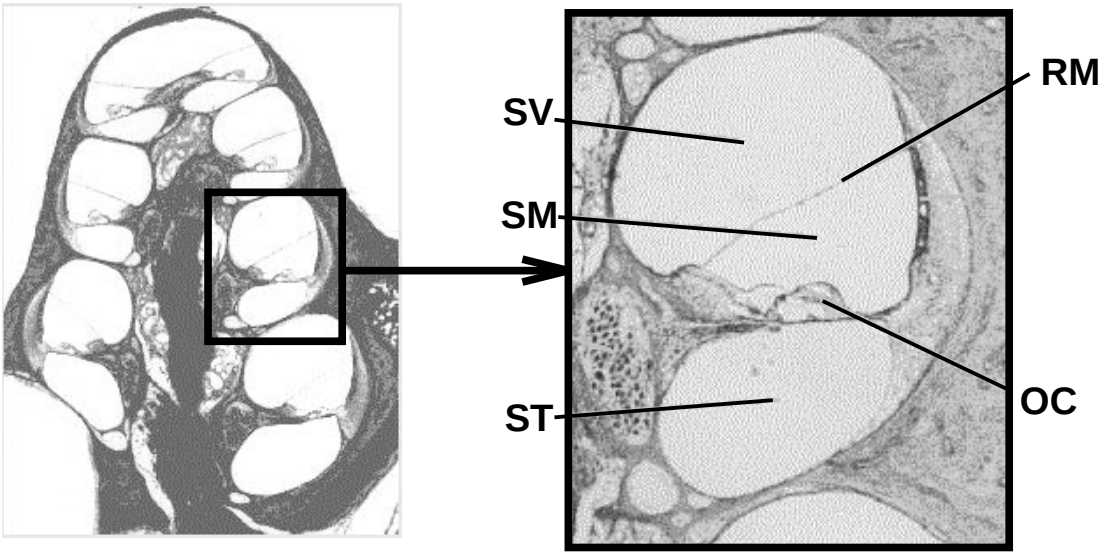


**Figure 2:** A cross-section of the entire cochlea (a) and of the cochlear tube (b).
SV: scala vestibuli, SM: scala media, ST: scala tympani, RM: Reissner's membrane, OC: organ of Corti.

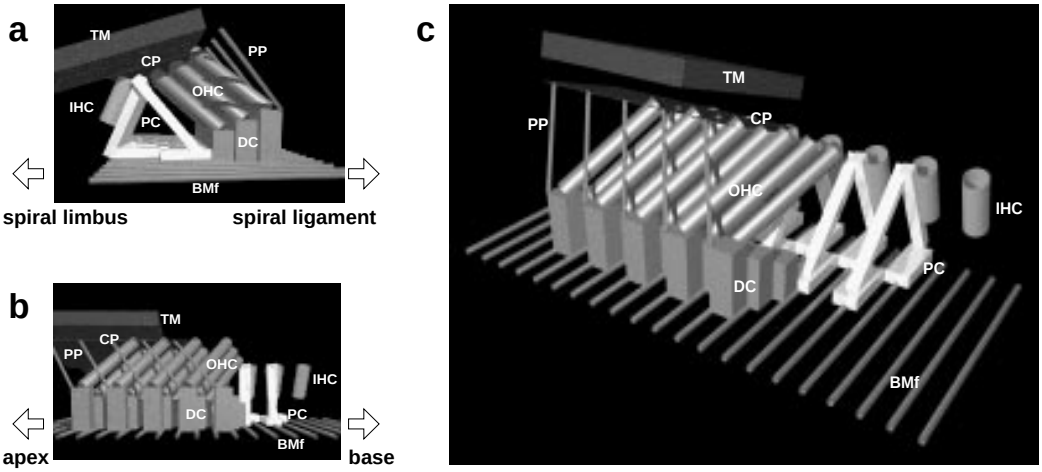


**Figure 3:** A schematic representation of the organ of Corti situated on the basilar membrane viewed from different directions. (a) can be compared with the radial cross-section of the real cochlea shown in Fig. 2 , (b) and (c) clearly show the slanting of the various cells in longitudinal direction.
BMf: basilar membrane fibers, PC: pillar cells, IHC: inner hair cells, OHC: outer hair cells, DC: Deiters cells, PP: phalangeal processes of Deiters cells, CP: cuticular plate, TM: tectorial membrane.

the mechanical properties of the cochlear partition and its interaction with the surrounding fluid. As Fig. 2 and the schematical representation in Fig. 3 indicate, the organ of Corti situated on the basilar membrane contains a number of different cells in a specific geometrical construction.

First we see a row of bony pillar cells. There are two types, inner (IPC) and outer (OPC) pillar cells. Together these cells form the tunnel of Corti

which is the heart of the organ of Corti and which supports the surrounding cells. The tunnel of Corti separates the inner hair cells (IHC) from the three rows of outer hair cells (OHC). These hair cells are of major interest to the actual hearing process, because they transform mechanical stimuli into nerve signals. As the name suggests these cells posses hairs, positioned in hair bundles on top of the cells. A deflection of such a hair bundle leads to a change in the transducer current of the hair cell, which controls the generation of action potentials of nerve cells connected to the hair cell bottom. These nerve cells carry the information to the brain via the auditory nerve. The innervation by nerve cells of these two types of hair cells (IHCs and OHCs) is very different, and may provide a clue about their separate roles in the hearing process. Each IHC is primarily innervated by several afferent nerve fibers, transporting information from the hair cell to the brain. The OHCs on the other hand have very few afferent nerve fiber connections, but are mainly innervated efferently. This means they do not give information to the brain, but instead receive information from it. This seems illogical, since the main purpose of a hair cell most likely is the encoding of the mechanical stimulation in nerve signals that can be analysed by the brain. If, however, this information can not be transported to the brain, due to a lack of afferent innervation, the OHCs seem obsolete. It is, of course, very unlikely that a cell type with such an apparent specialised construction and placement in the organ of Corti, and moreover outnumbering the IHCs by a factor three, would serve no significant purpose in the process of hearing. On the contrary, the integrity of the OHCs plays a crucial role in the functioning of the cochlea. Administration of ototoxic drugs like kanamycin have been shown to destroy OHCs (selectively) and produce a dramatic reduction in cochlear selectivity and sensitivity [1] (e.g. Kiang *et al.*, 1986). Carlyon and Beveridge (1994) showed that administering aspirin (acetylsalicylic acid, or "salicylate") produces a similar effect, probably by affecting the electrical properties of OHCs (Tunstall *et al.*, 1994). Yet another indication of the importance of the OHCs was given by Guinan and Gifford (1988). They showed that manipulating the efferent input to the OHCs induced changes in the selectivity and sensitivity of the afferent output of the IHCs.

More light was shed on the function of the OHCs in the action of the cochlea by the discovery of OHC-motility. Studies by e.g. Brownell *et al.* (1985), Ashmore (1987) and Brundin *et al.* (1989) show that isolated OHCs respond to sinusoidally varying electric fields or pressures created by a water jet, by both phasic and tonic [2] length changes of the cell body. The exact

[1] The term selectivity is used to describe the ability to detect frequency differences, sensitivity refers to the threshold of hearing i.e. the lowest level at which a sound can still be detected.

[2] phasic=a.c.=following the frequency of stimulation, tonic=d.c.=a constant length change during the entire stimulus interval

mechanism behind these length changes, or how they affect the mechanics of the organ of Corti is still subject to debate and investigation, but *in vivo* measurements indicate that OHC length changes also occur during the normal hearing process (Brundin *et al.*, 1992).

The role of the Deiters cells, and of the Hensen and Claudius cells (covering the BM on the side of the spiral ligament, not shown in Fig.3) is not very clear. It is generally assumed that these cells only provide support for the OHCs.

The last important structure to be described in a cross-section of the cochlea is the tectorial membrane (TM). This structure lies on top of the organ of Corti and covers the hair bundles of inner and outer hair cells. Because it is connected to the bony spiral limbus at a different point than the basilar membrane, movement of the cochlear partition in a direction perpendicular to the BM will result in a shearing motion between the cuticular plate and the TM. This results in bending of the hair bundles of the OHCs and IHCs and thus leads to a nerve signal to the brain. The exact transition from the movement of the cochlear partition to the bending of the hair bundles is not clear yet. There is uncertainty about the nature of the shearing motion between the cuticular plate, which covers the top of the organ of Corti, and the lower side of the TM. In most descriptions of this shearing motion both the cuticular plate and the TM are portrayed as rigid structures. The shearing motion between both structures must, however, exhibit a pronounced three-dimensional character. The motion of the cuticular plate will have a 3-D nature due to the geometry of the organ of Corti. For the case of the TM, there is also sufficient evidence to assume that its motion differs from a simple rigid body rotation. Morphological data show that it contains a complicated internal structure. It is therefore not inconceivable that the TM will even have its own mode of vibration. (This is actually used by some modellers as an explanation of some of the properties of the cochlea, see chapter 6.) Measurements of the motion of the cuticular plate and the TM, such as performed by Ulfendahl *et al.* (1995) are necessary to shed light on this aspect of cochlear mechanics.

But even if the shearing motion would be known exactly, the question still remains how this relates to the bending of the hair bundles of both IHCs and OHCs. Imprints of hair bundle tops found in the bottom of the TM at the position of the OHCs indicates that there is a direct mechanical coupling . This would imply that the relative displacement between the cuticular plate and the TM is the stimulus to the OHCs. No such imprints have been found at the locations of the IHCs. This would suggest that the IHC hair bundles are deflected due to the fluid flow in the subtectorial space, created by the shearing motion. In that case the IHCs would respond to the relative velocity instead of the displacement between cuticular plate and TM. The presence of a small ridge named Hensen's stripe underneath the TM right above the IHC hair bundles and tiny string-like fragments connecting this stripe to the cuticular plate between the IHCs probably plays a role in the conversion of

the shearing motion into fluid flow and into IHC hair bundle deflection.

## 1.2 The three-dimensional structure of the cochlear partition

The cells in the cochlear partition are placed in a complex three-dimensional arrangement (see Fig. 3 ). The basilar membrane is made up of fibers running radially from the spiral limbus (on the inside of the turns of the cochlea) to the spiral ligament (on the outside of the turns). The pillar cells are connected to these fibers, with their footplates also in radial direction. (There are indications that in the high frequency region the inner pillar cells may actually be placed on the bony limbus.) The inner and outer pillar cells are connected at the heads, but their footplates are positioned next to one another in such a way that the footplate of the OPC is on the apical side of the footplate of the IPC. The exact nature of the connection of the heads is not known. There seems to be a quite tight connection, but there might be some freedom for rotation in the plane perpendicular to the longitudinal direction. The inner hair cells are placed against the inner pillar cells, with their cell bodies placed approximately vertical.

The outer hair cells are all individually connected to a Deiters cell at their base and make up part of the cuticular plate with their tops. The rest of the cell body is surrounded by cochlear fluid (probably perilymph from the scala tympani), which is also present in the tunnel of Corti between the pillar cells. The OHC cell bodies are placed at angles with the normal of the basilar membrane, both in longitudinal and in radial direction. In radial direction the OHCs are slanted towards the spiral limbus following the outer pillar cells. In longitudinal direction the OHCs are slanted in basal direction, placing the top of an OHC a few $\mu$m (approximately one hair cell width) basal [3] to its base. Furthermore, the rows of OHCs are not aligned in radial direction and even the hair bundles are at an angle with the hair bundles of the IHCs. The hairs on top of an IHC are positioned in a straight line parallel to the longitudinal axis of the cochlear channels. The hair bundle of an OHC is W-shaped, with the "line" of the W not parallel with the IHC hair bundles, but slightly slanted. The Deiters cells serve as support for the OHCs and are assumed to be firmly connected both to the bases of the OHCs and to the basilar membrane. These cells have so-called phalangeal processes, thin fibers running from the top of a Deiters cell to the cuticular plate. They do so at the same angle as the OHCs in radial direction, but in longitudinal direction they extend to a position approximately 10 $\mu$m more apical. So through an OHCs tilted cell body and

[3]The basal direction in the cochlea is the direction towards the middle ear, along the cochlear turns. The other direction, towards the helicotrema, where the scala vestibuli and the scala tympani are connected, is called apical.

the phalangeal process of its supporting Deiters cell, the tops of OHCs 2 cells (20 $\mu$m centre to centre) apart are connected.

Finally, the Hensen cells and Claudius cells have no reported special arrangement, but seem to serve as a boundary between the two types of cochlear fluid. It is generally assumed that the top surfaces of the IHCs, the pillar cells, the OHCs and the Hensen cells, together making up the cuticular plate, form an impermeable boundary between the endolymph above and the perilymph underneath the cochlear partition.

The last part of the structure of the cochlear partition to be described is the tectorial membrane (TM). This sheath covering the cuticular plate is a complicated structure on its own. It is, for example, reported to possess an internal structure of fibers running in different directions. One layer of fibers that can clearly be observed is running at an angle with the radial direction that puts these fibers approximately perpendicular to the slanted OHC hair bundles. As mentioned in the previous section, many of the mechanical properties of the TM are still unknown and even details about its morphology, such as the connections with the cuticular plate, are still uncertain. Imprints found on the lower surface of the TM suggest a tight connection with the tops of the hair bundles of the OHCs (e.g. Dunnebier *et al.*, 1995). How exactly Hensen's stripe, directly above the IHCs, and the end of the TM are connected to the cuticular plate, can only be speculated on.

A further complication of this intricate 3D arrangement of cells in the cochlear partition is a variation of angles and sizes along the length of the cochlea. To give a few examples: the width of the cochlear partition itself changes from less than 0.1 mm to 0.4 mm, the angle between the basilar membrane and the cuticular plate changes from 3.5 to 35 degrees and the length of the hair bundles of IHCs changes by a factor of 2 from base to apex (in OHCs this factor is even larger, up to 10) (Wever, 1970; Lim, 1986; Pujol *et al.*, 1991).

Considering the complexity of the cochlear partition it should be no surprise that some simplifications have to be made in order to arrive at a workable model.

# The cochlea in action

As described in the previous section the cochlea transforms an incoming mechanical (acoustical) stimulus into a nerve signal. The cochlea performs sophisticated pre-processing on the stimulus, however, before converting it into a spike train sent up the acoustic nerve. First, the cochlea performs a frequency analysis by spreading the incoming signal along the cochlear partition, with the high frequencies exciting the basal part and lower frequencies exciting more apical parts. This is done with a fairly high degree of accuracy. Subjects can discriminate frequency differences of down to 1 %, and this sharp frequency discrimination is believed to originate partly from the excitation patterns of the cochlear partition [1].

As discussed in section 1.2 the mechanical parameters of the cochlear partition vary along the length of the cochlea. It is the generally accepted idea that these variations and the interaction with the cochlear fluids creates a pattern described as a travelling wave along the cochlear partition, if the cochlea is stimulated with a pure tone. This travelling wave (first shown by von Békésy, 1960) decreases in propagation speed and increases in amplitude until it reaches a point of maximum excitation, the location of which depends on the frequency of the tone. This place is called the characteristic place of that frequency. Because each frequency has its own characteristic place, a place-frequency map arises on the cochlear partition. The accuracy with which frequency differences can be perceived depends on the amount of overlap between the excitation patterns of the travelling waves for different frequencies.

The cochlea also compresses the extensive dynamic range of hearing (over 120 dB [2]) down to the dynamic range of the nerve cells (approx. 40 dB). The cochlea begins detecting signals around 0 dB SPL or even a bit lower for frequencies in the mid-audio range (1 to 4 kHz). In order to measure

[1] The excitation patterns on the cochlear partition do not fully explain the frequency discrimination we are able to perform. Information about the frequency of an incoming signal is also encoded in the firing pattern of the neurons attached to the hair cells. (This 'phase-locking' of the nerve signals works best for frequencies below $\approx 1$ kHz, for higher frequencies it apparently becomes harder for the nerves to follow the frequency of the stimulus.)

[2] The decibel scale gives levels on a logarithmic scale. For example a pressure level is usually expressed in dB SPL: decibel sound pressure level. The dB SPL scale is related to the normal pressure in Pa by:

$$L = 20 \log(p/p_0) \tag{1}$$

where $p_0 = 2 \cdot 10^{-5}$ Pa is the standardised reference pressure. A range of 120 dB therefore means a factor $10^6$ in pressure amplitude. Note that these levels relate to pressure *differences* from the normal atmospheric pressure.

these detection limits a listener has to be placed in a special sound proof room, because the normal noise from our everyday environment easily exceeds 40 dB SPL. The pain limit lies somewhere around 120 to 130 dB SPL.

In order to perform this incredible compression task the cochlea must operate in a non-linear manner. At high levels of stimulation the movement of the cochlear partition saturates, probably also to protect the vulnerable tissues in the cochlear partition. At the other end of the scale the cochlea is believed to actively amplify input at very low levels of stimulation, in order to make them detectable. The origin and nature of this amplification process have been the focus of fiery debate for years. It is now generally accepted that the outer hair cells play an important role in this process. Not only because they seem to have no role in passing on information to the brain, but mainly because these cells can change their body length when stimulated acoustically or electrically. However, how this would work in a real *in vivo* cochlea and how this behaviour of the OHCs affects the action of the cochlea has still to be determined. Other sources of (mechanical) active behaviour in the cochlea have not been identified (yet), and therefore the hypothesis of OHCs being the source of mechanical active amplification still stands firmly. This does not mean that this view is undisputed. There are scientists who do not even accept the idea that the cochlea needs to be generating energy (e.g. Allen and Fahey, 1992). Other scientists argue that the motility of the OHCs can not operate fast enough to produce amplification at high frequencies (e.g. Dallos, 1992; Santos-Sacchi, 1992).

The fact that the cochlea produces energy is, however, accepted by most scientists now. One of the most important proofs comes from the field of otoacoustic emissions. In general otoacoustic emissions (OAEs) are very weak sounds generated by the cochlea. The amazing discovery that the cochlea is capable of producing sound, along with being able to detect it was made in 1978 (Kemp, 1978). Since then many types of OAEs have been classified. Most of these are responses by the cochlea to different forms of (low level) stimulation. An exceptional class is formed by the spontaneous otoacoustic emissions (SOAEs), also discovered by Kemp (1979). These emissions do not need triggering by any external stimulation, but, as the name indicates, occur spontaneously. OAEs (evoked and spontaneous) are emitted into the ear canal and from there into the world at such a low level that they can not be picked up unless a very sensitive microphone is placed in the ear canal. Generally evoked otoacoustic emissions (EOAEs) depend on the level of the stimulus, but they have an upper limit of about 20 to 30 dB SPL. SOAE levels usually are around 0 dB SPL, with an upper limit of about 10 dB SPL. One has to bear in mind that these are levels measured in the ear canal and in order to do so the ear canal has to be sealed off from the outside world by an acoustic coupler containing the probe. Sealing off the ear canal in such a way can increase the levels of emissions by more than 10 dB (Zwicker, 1990; van den

Raadt, 1993).

Both types of OAEs have been studied extensively over recent years, with the hope that they might shed some light on the internal mechanisms at work in the cochlea. The mechanisms that make the cochlea the best sound receiving system known so far. At first SOAEs were thought to occur only in some ears and indicate cochlear damage offsetting the cochlear amplification mechanism (e.g. Ruggero, 1983). The increase in occurrence rate that accompanied refined measurement techniques, however, leads to the conclusion that SOAEs are a feature of a healthy cochlea. This is supported by the measurements of SOAEs in new-borns indicating an even higher occurrence rate (Kok *et al.*, 1993). This has only increased the interest in SOAEs and as measurement methods became more refined more and more details about them came to light. Some of these details seem to invite scientists to stretch their explanatory imagination to the limit. For example the fact that SOAEs occur more frequently in the ears of females than in the ears of males. There also seems to be a slight prevalence of SOAEs for the right ear. SOAEs do not negatively affect a person's hearing and are never actually perceived by the owner. There is no relationship between SOAEs and the "ringing" of the ear, often perceived after exposure to high sound levels.

All otoacoustic emissions that do not occur spontaneously are evoked by some sort of stimulus presented to the ear, hence the name evoked otoacoustic emissions. Because the emission is measured by a microphone inserted in the ear canal, where the stimulus is also presented, the measured signal will contain both emission and stimulus. Somehow these two signals have to be separated. There are essentially two ways to do this: in the time domain, or in the frequency domain. Separating stimulus and emission in the time domain is done by using a stimulus of a very short duration (a few milliseconds). The signal measured by the microphone is then divided in time into a stimulus part and an emission part. Examples of such *delayed* evoked otoacoustic emissions are click evoked otoacoustic emissions (CEOAE) and tone burst evoked otoacoustic emissions (TBEOAE). An example of separation of stimulus and emission in the frequency domain are distortion product otoacoustic emissions (DPOAE) that result when a stimulus containing more than one frequency component is presented. The formation of distortion product frequencies in the cochlea was known from psychophysical measurements for a long time, but they were not measured in the ear canal until after the discovery of OAEs. A well-known psychophysical demonstration of the formation of distortion products is to produce a sound stimulus consisting of two sine-waves with frequencies $f_1$ and $f_2$ ($f_1 < f_2$). If $f_1$ is kept constant and $f_2$ increased in frequency a listener will hear a third tone going down in frequency. Since this tone is not present in the stimulus it has to be formed somewhere in the auditory system. The frequency of this third tone is $2f_1 - f_2 (= f_1 - (f_2 - f_1))$ and it originates in the cochlea due to the non-linear processing of the inco-

ming signal. DPOAEs are therefore an excellent tool to study the non-linear behaviour of the cochlea.

The clinical use of otoacoustic emissions is demonstrated by the fact that subjects with cochlear hearing deficits have emissions that differ from those found in normal hearing subjects. In the classical way to test the functioning of the hearing system subjective thresholds are determined at standardised frequencies and related to standardised average thresholds. Unfortunately these tests can not be performed on subjects incapable of responding, such as babies and small children. Another problem is the fact that this method tests the functioning of the entire hearing system, not only of the cochlea. (The result of the entire hearing system is of course all that matters to a patient, but in order to improve the diagnosis of a hearing deficit it would be useful to separate the functioning of the cochlea from the neural processing.) If otoacoustic emissions can be directly linked to cochlear functioning this opens the possibility of an objective test of only this step in the hearing process, that can be performed on any subject.

# Cochlear modelling and this thesis

Ever since the first measurements of the action of the cochlea by von Békésy (collected in von Békésy, 1960), attempts have been made to model the function of this complicated organ. (See Zwislocki, 1950, for some of the pioneering work in this field.) The idea governing cochlear modelling is, of course, that all the characteristics of the cochlea can be simulated by a, more or less simplified, mathematical or numerical model. The main motivation for this line of research is found in what can be termed 'truth approximation' or 'realism': the assumption that if a model produces results similar to those of the real system, it probably does so in a manner similar to the real system. It is for this reason that cochlear modelling can eventually be of diagnostic value. In a model it is relatively easy to identify the structures or processes responsible for a certain type of response [1]. If these structures or processes can be related to e.g. cells or substances present in the real cochlea, this will give clues about the function and importance of these cells or substances. It is for reason of this 'realism' that cochlear modellers try to construct a model as close to the real cochlea as possible, so that individual parts of the model can be identified as (models of) actual structures. It is usually the lack of computer strength/time and/or the desire to use analytical methods that limits the complexity of a cochlea model, and thereby its congruence with the real cochlea.

One of the most promising areas where cochlea models may have a future as a diagnostic tool is in the explanation of the mechanisms underlying otoacoustic emissions. It is generally believed that these emissions can supply valuable information about the internal state of the cochlea. The main problem is still in the interpretation of emission data. If emissions can be properly simulated by a cochlea model and details about them described in terms of structures and mechanisms in the model, the correspondence between model structures and physical structures in the real cochlea can be used to extract information about the interior of the cochlea without actually 'looking inside'.

The work described in this thesis can be divided into two lines of research. Part II describes computations performed with a 'simple' one-dimensional cochlea model. This model has the advantage that it is not too complex to understand and leads to a numerical code that does not require much computer time and memory. Because of the aforementioned importance of otoacoustic emissions this field was chosen as the area of application of the one-dimensional

[1] As can be seen in sections 5.3 and 6.2 identifying the processes underlying a certain type of model behaviour can be quite complicated. However, similar investigations in the real cochlea are absolutely impossible, due to the vulnerability of the organ.

model in this thesis. The fact that the model computes the behaviour of the cochlea in the time domain makes it especially useful for the study of nonlinear effects, which play an important role in many otoacoustic emissions. After a description of the model in chapter 4, in chapter 5 the question whether or not there exists a form of spatial periodicity in the cochlea is adressed. This question arises from the modelling of toneburst- and click-evoked otoacoustic emissions and a possible answer is found in the modelling of spontaneous otoacoustic emissions. In chapter 6 distortion product otoacoustic emissions are investigated. To be more exact, the question whether or not a filtering effect observed in the level of these emission reflects the existence of a physical filtering structure locally in the cochlea is answered. In order to arrive at this answer the generation of this type of emission is studied in detail. A conclusion that can be drawn from these two chapters is that the behaviour of the phase in the cochlea model plays a crucial role in determining the answers to both the question of spatial periodicity based on SOAEs and of the 'second filter' in DPOAEs. Chapter 7 is dedicated to the importance of the phase-behaviour and how its influence on these two effects in otoacoustic emissions might be used to determine the phase-behaviour of the real cochlea.

In part III a different line of investigation is started. The main disadvantage of the one-dimensional model is its simplified description of the cochlear partition. This makes it difficult to relate processes in the model to structures or even individual cells or cell types in the real cochlea. In order to arrive at a model in which a distinction can be made between the various structures and cells in the cochlear partition, a so-called micromechanical model has to be developed. It is, however, my clear conviction that such a model is useless if the cochlea is treated one-dimensionally. Therefore, the possibility of a three-dimensional treatment with the aid of a finite element method is investigated first. The choice was made to use a commercially available finite element package, because of the included possibilities to use complex 3-D geometries and/or different equations governing the fluid behaviour (Laplace or Navier-Stokes). In chapter 9 a model of a cupula in the lateral line canal in a fish is constructed, as an intermediate step. The motion of this cupula is driven by the fluid motion in the canal and described by a single equation of motion. This is a simplification with respect to the cochlea model in which there is a large number of moving structures. The description of the fluid, however, is more complex in this case: the incompressible Navier-Stokes equations have to be used, whereas in the case of the cochlea the Laplace equation suffices. The results of this first trial were promising enough to validate the attempt to arrive at a three-dimensional version of the cochlea model, described in chapter 10. Although the results of this model are encouraging it is clear that computational requirements severely restrict the application of this model. Finally in chapter 11 the equations of motion to be used in a three-dimensional micromechanical model of the cochlear partition are derived.